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THESIS

DEVELOPMENT OF A COMPUTER PROGRAM FOR THE TESTING AND EVALUATION OF NUMERICAL OPTIMIZATION TECHNIQUES

by

James Edward Fitzgerald, III

June 1982

Thesis Advisor: G. N. Vanderplaats

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A major portion of this work is the software (user guide) which is presented in detail with examples and results. Explanation of how this code is coupled to an optimizer is given.

Design variables are member area sizes, joint coordinates, or both. Examples are presented to demonstrate the method.

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Development of a Computer Program for the Testing and Evaluation of Numerical Optimization Techniques

by

James Edward Fitzgerald III
Lieutenant, United States Navy
B.S., Middle Tennessee State University, 1975

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

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A three dimensional finite element code is written for truss analysis and design. Trusses may be designed for minimum weight subject to constraints on: member stresses, Euler buckling, joint displacements and system natural frequency. The optimum configuration may be found in addition to optimization with respect to member sizes.

The finite element code may be used as a stand alone analysis tool or may be coupled to an optimizer of the user's choice. The finite element displacement method of analysis is used for static analysis and eigenvalues are calculated using the subspace iteration technique.

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I. INTRODUCTION

Design optimization requires the minimization or maximization of some parameter. Optimization of structures has had continuing changes since its development in the early 1960's with an active area of research being elastic truss structures. The main goal is to design structural systems that efficiently perform specified purposes. For any design to be acceptable, it must satisfy a variety of physical, aesthetic and economic constraints.

Since most physical problems can be modeled by some mathematical formulation a computer program can be written to perform the necessary calculations.

The purpose of this research was to develop a FINITE ELEMENT code that could be easily coupled to an optimizer, thus (1) allowing testing and comparison of various optimizers and (2) provide a useful design program in its own right.

The design problem considered in this study is the optimization of three-dimensional indeterminate trusses, for multiple static load conditions. The objective is to minimize the weight of the structure where the design variables are member sizes and joint coordinates. Constraints include stress, displacement, Euler buckling, and the natural frequency of the system.

This document describes the use and capabilities of the finite element computer code to be coupled to an optimizer. The user's manual presented in Chapter V contains a simple design example in which the program is coupled to the CONMIN optimization code [Ref. 1].

Additionally, guidelines for coupling the code to an optimizer of the user's choice are presented.

Several examples demonstrating the program under a variety of conditions are presented. Conclusions and recommendations for future work are given.

II. OPTIMIZATION

A. INTRODUCTION

The main goal of structural engineering optimization is to design structural systems that efficiently perform specified purposes. Selection of a specific algorithm must include the following considerations: 1) the structure should be analyzed as few times as possible, 2) the algorithm should minimize specific gradient information required, and 3) it should provide reasonable assurance that an optimum design will be reached.

The next few sections discuss the general formulation of the algorithm with respect to the above requirements.

B. FORMULATION

Minimum weight design of trusses is presented in the general form of a mathematical programming problem as follows:

$$\text{Minimize } F(X) \qquad \text{(Eq. 1)}$$

Subject to:

$$g_j(x) \leq 0 \qquad j=1,m \qquad \text{(Eq. 2)}$$

$$x_i^{\ell} \leq x_i \leq x_i^{u} \qquad i=1,n \qquad \text{(Eq. 3)}$$

where F(X) is the objective function, in this case, weight of the structure be minimized. X is the vector of independent design variables and here contains the member cross-sectional areas as well as the coordinates of the joints. The inequality

constraints, $g_j(x) \leq 0, j=1,m$, must be satisfied for the design to be accepted as feasible. These include limits on stress, Euler buckling, joint displacements and the first fundamental frequency of the structure. Side constraints x_i^ℓ and x_i^u are lower and upper bounds on the design variable. These may be treated as general inequality constraints.

C. PARAMETERS

The design variables, constraints, and objective function considered in the design process are discussed here.

1. Design Variables

The design variables the user has available are member cross-sectional area, reciprocal of member cross-sectional area, joint coordinates, or both member areas (or their reciprocals) and coordinates. The cross-sectional areas are A_k, $k=1,NE$, where NE is the number of elements in the truss structure. The joint coordinates are X_{ij}, $i=1,2,3$ $j=1, NJ$, where i is the coordinate axis, j is the joint number and NJ is the total number of joints. Design variable linking is allowed in both member sizing and coordinate design variables.

2. Objective Function

The objective function considered here is weight.

$$\text{Weight (W)} = \sum_{i=1}^{NE} \rho_i AL_i \qquad \text{(Eq. 4)}$$

where ρ is the material density, A is the cross-sectional area and L_i is the length of the member. The truss may be made up of members of differing materials.

3. Constraints

Stress: $$\frac{\sigma_{ij}}{\bar{\sigma}^{-}} - 1 \leq 0 \qquad i=1,NE \quad j=1,NLC \qquad \text{(Eq. 5)}$$

$$\frac{\sigma_{ij}}{\bar{\sigma}^{+}} - 1 \leq 0 \qquad i=1,NE \quad j=1,NLC \qquad \text{(Eq. 6)}$$

where σ is the stress in member i under load condition j. NE is the number of elements and NLC is the number of loading conditions.

$\bar{\sigma}^{-}$ is the lower bound on the stress (maximum compressive stress) and $\bar{\sigma}^{+}$ is the upper bound on the stress. The upper and lower bounds on stress may be different for each member, but are taken to be the same for every loading condition.

4. Euler Buckling

The stress at which Euler buckling occurs is given by:

$$\sigma_i^{E} = \frac{-K_i A_i E_i}{L_i^{2}} \qquad i=1,NE \qquad \text{(Eq. 7)}$$

where the subscript i corresponds to the member number, E_i is Young's modulus and K_i is a constant depending on the cross-sectional geometry of the member.

5. Displacement

Displacement limits are imposed at prescribed joints to create a constraint equation as follows:

$$\frac{u_{ijk}}{\bar{u}_{ijk}^{-}} - 1 \leq 0 \qquad \text{(Eq. 8)}$$

$$\frac{u_{ijk}}{\bar{u}_{ijk}^{+}} - 1 \leq 0 \qquad \text{(Eq. 9)}$$

where $\bar{u}_{ijk}^{-}$ and $\bar{u}_{ijk}^{+}$ are lower and upper bounds on the displacement at joint i in the coordinate direction j under loading condition k.

6. Frequency

The first fundamental frequency of the structure is required to exceed the specified lower bound, so that

$$1 - \lambda/\bar{\lambda} < 0 \qquad \text{(Eq. 10)}$$

Reference 2 is an excellent source for the basic structural design formulation.

III. FINITE ELEMENT METHOD

A. INTRODUCTION

Several features are desirable when the finite element methods of analysis are used in design optimization. First the number of analyses for the structure should be kept to a minimum. Second, the amount of gradient information required during the design process should be reduced to shorten run times and computer storage requirements. Third, the user should be able to specify only that gradient information desired.

B. ANALYSIS

Initial problem formulation includes member sizing, material properties (which may be different for each member), a set or sets of external loads, and specified support condition.

The analysis for the stresses and deflections must satisfy the conditions of equilibrium of forces at the nodes and compatibility of deformation. In this analysis the weight of the individual members are not part of the specified load conditions.

Additionally for this analysis the following assumptions are made. Trusses will be treated as discrete elements, and each element will be treated as pin-connected with loads and reactions supported at the joints.

The general method of solution is as follows. The Displacement (Stiffness) method reference 2 considers the joint displacement components as the unknowns, and written in matrix notation for the general case is

$$\underset{\approx}{K}\underset{\sim}{u} = \underset{\sim}{P} \qquad \text{(Eq. 1)}$$

where $\underset{\approx}{K}$ is the global stiffness matrix, $\underset{\sim}{P}$ is the vector or vectors of applied loads, and $\underset{\sim}{u}$ is the vector of vectors of displacements.

Once displacements at every node are known, the internal forces and stresses are calculated by applying the appropriate force-deflection relationships.

When the system's natural frequency constraints are considered the design process requires the solution of an eigenproblem. This solution will determine the natural frequencies and normal modes of the structure. For linear elastic structures, the finite element approach leads to the following equation of motion with free vibration conditions,

$$\underset{\approx}{M}\underset{\sim}{\ddot{u}} + \underset{\approx}{K}\underset{\sim}{u} = 0 \qquad \text{(Eq. 2)}$$

where $\underset{\approx}{M}$ is the global mass matrix, and $\underset{\sim}{\ddot{u}}$ is the linear acceleration vector. This leads to an eigenvalue problem of the form $lK-\lambda\ ld=0$, and is solved here by the subspace iteration method reference 2.

C. GRADIENTS OF CONSTRAINTS

Gradient computation of necessary functions in a design optimization process arise from the need for derivative information for efficient mathematical programming. For structural optimization the gradient of displacement with respect to the design variables, $\partial u/\partial x$, is needed from which ∇G, is calculated for stress, displacement, and buckling.

Consider the finite element method $\underset{\approx}{K}\underset{\sim}{u} = \underset{\sim}{P}$. Taking the derivative of both sides with respect to the design variable x_ℓ, we have:

$$\frac{\partial}{\partial x_\ell} [\underset{\approx}{K}\underset{\sim}{u}] = \frac{\partial}{\partial x_\ell} (\underset{\sim}{P}) \qquad \text{(Eq. 3)}$$

Assuming the loads P are not a function of x_ℓ,

$$[\frac{\partial}{\partial x_\ell} (\underset{\approx}{K})] (\underset{\sim}{u}) + \underset{\approx}{K} \frac{\partial}{\partial x_\ell} (\underset{\sim}{u}) = 0 \qquad \text{(Eq. 4)}$$

Finally, we arrive at $\frac{\partial}{\partial x_\ell} (\underset{\sim}{u}) = -\underset{\approx}{K}^{-1} [\frac{\partial}{\partial x_\ell} (\underset{\approx}{K})] \underset{\sim}{u}$ (Eq. 5)

where K^{-1} is the inverse of K. For efficiency K^{-1} is not actually calculated.

IV. PROGRAM FEATURES

A. INTRODUCTION

Each computer code has its own special features with which the user should be familiar if the program is to be used effectively. The next few sections will discuss an overview of the code and a typical problem that might be solved using the program. This problem along with other numerical examples will be presented in detail with results in Chapter VI.

The FINITE ELEMENT code was written to be used as a stand alone analysis program or an analysis code that could easily be coupled to an optimizer (of the user's choice) through simple modifications to the main driver program.

With user supplied area and coordinates coupled with input control parameters, the analysis mode will calculate the weight of the truss structure. Design variables may be chosen as member areas, joint coordinates, or both. Additionally, gradient information will be calculated with respect to area variables, coordinate variables or both. Coupled to an optimizer the code will optimize the weight of the structure and print the final optimization information and gradient vectors of specified constraints.

The following example of a 25-bar space tower presented in Tables (I-IV) shows some of the options the code contains.

Table I

25-BAR TOWER SAMPLE OUTPUT

INPUT CONTROL PARAMETERS

```
INPUT PARAMETERS FOR STRUCTURAL ANALYSIS AND DESIGN ROUTINE, "SAD"
25-BAR SPACE TRUSS (TEST CASE STRESS/DISP./BUCKLING/FREQ.)


CONTROL PARAMETERS


NUMBER OF ELEMENTS, NE            =    25
TOTAL NUMBER OF JOINTS, NJ        =    10
JOINT CONSTRAINT VARIABLE, NCJ =    10
NO. OF MATERIAL TYPES, NMT        =     1
NO. OF LOAD COND., NLC            =     2
NO. OF EIGENVALUES, NEIG          =     2
NO. OF EIGENVALUES CALC., NEIG1=     2
NO. OF FIXED MASSES, NFMASS       =     2
BUCKLING CONSTRAINT ID, NEUBC     =     1
NO. OF DISPL. CONST.,NDSPLC       =     4
NO. OF FREQ. CONST., NFREQ        =     1
LUMPED MASS OPTION, LMASS         =     0
VARB. CALC. CONTROL , IDVCLC      =     2


ACCELERATION DUE TO GRAVITY, GRAV          = 0.38640E+03
EIGENVALUE CONVERGENCE TOLORANCE, EPSEIG = 0.10000E-03

JOINT COORDINATES
JOINT          X                    Y                   Z
  1      -0.37500E+02     0.0                    0.20000E+03
  2       0.37500E+02     0.0                    0.20000E+03
  3      -0.37500E+02     0.37500E+02            0.10000E+03
  4       0.37500E+02     0.37500E+02            0.10000E+03
  5       0.37500E+02    -0.37500E+02            0.10000E+03
  6      -0.37500E+02    -0.37500E+02            0.10000E+03
  7      -0.10000E+03     0.10000E+03            0.0
  8       0.10000E+03     0.10000E+03            0.0
  9       0.10000E+06    -0.10000E+03            0.0
 10      -0.10000E+03    -0.10000E+03            0.0

COORDINATE DESIGN VARIABLES
      DESIGN VARIABLE                      MULTIPLIER
JOINT      X     Y     Z           X                Y               Z
  1        0       0      0       0.0            0.0              0.0
  2        0       0      0       0.0            0.0              0.0
  3        1       2      3     -0.1000E+01      0.1000E+01      0.1000E+01
  4        1       2      3      0.1000E+01      0.1000E+01      0.1000E+01
  5        1       2      3      0.1000E+01     -0.1000E+01      0.1000E+01
  6        1       2      3     -0.1000E+01     -0.1000E+01      0.1000E+01
  7        4       5      0     -0.1000E+01      0.1000E+01      0.0
  8        4       5      0      0.1000E+01      0.1000E+01      0.0
  9        4       5      0      0.1000E+01     -0.1000E+01      0.0
 10        4       5      0     -0.1000E+01     -0.1000E+01      0.0


MATERIAL PROPERTIES
CODE        E            RHO          SIG-MIN        SIG-MAX       K-EULER
  1   0.1000E+08   0.1000E+00  -0.4000E+05    0.4000E+05   0.3927E+02
```

Table II

25-BAR TOWER SAMPLE OUTPUT

```
JOINT DISPLACEMENTS CALCULATED BY SYSTEM ROUTINE "SAD"

LOAD CONDITION     1

DISPLACEMENTS      DEGREE OF FREEDOM
JOINT          1               2               3
    1    -0.21905E-02     0.38017E+00    -0.27099E-01
    2     0.21910E-02    -0.38017E+00    -0.27099E-01
    3     0.90789E-01    -0.15964E-01    -0.68752E-01
    4     0.91278E-01     0.17510E-01     0.36100E-01
    5    -0.90789E-01     0.15964E-01    -0.68752E-01
    6    -0.91278E-01    -0.17511E-01     0.36100E-01
    7     0.0             0.0             0.0
    8     0.0             0.0             0.0
    9     0.0             0.0             0.0
   10     0.0             0.0             0.0

LOAD CONDITION     2

DISPLACEMENTS      DEGREE OF FREEDOM
JOINT          1               2               3
    1     0.20126E-01     0.38860E+00    -0.21023E-01
    2     0.22911E-01     0.38860E+00    -0.32687E-01
    3     0.99531E-03     0.25951E-01    -0.95653E-01
    4     0.64733E-02     0.26707E-01    -0.10297E+00
    5     0.81493E-03     0.24435E-01     0.62874E-01
    6     0.66536E-02     0.25192E-01     0.70194E-01
    7     0.0             0.0             0.0
    8     0.0             0.0             0.0
    9     0.0             0.0             0.0
   10     0.0             0.0             0.0

JOINT COORDINATES
JOINT               X                  Y                   Z
    1       -0.37500E+02       0.0                 0.20000E+03
    2        0.37500E+02       0.0                 0.20000E+03
    3       -0.37500E+02       0.37500E+02         0.10000E+03
    4        0.37500E+02       0.37500E+02         0.10000E+03
    5        0.37500E+02      -0.37500E+02         0.10000E+03
    6       -0.37500E+02      -0.37500E+02         0.10000E+03
    7       -0.10000E+03       0.10000E+03         0.0
    8        0.10000E+03       0.10000E+03         0.0
    9        0.10000E+03      -0.10000E+03         0.0
   10       -0.10000E+03      -0.10000E+03         0.0

JOINT COORDINATES
JOINT               X                  Y                   Z
    1       -0.37500E+02       0.0                 0.20000E+03
    2        0.37500E+02       0.0                 0.20000E+03
    3       -0.37500E+02       0.37500E+02         0.10000E+03
    4        0.37500E+02       0.37500E+02         0.10000E+03
    5        0.37500E+02      -0.37500E+02         0.10000E+03
    6       -0.37500E+02      -0.37500E+02         0.10000E+03
    7       -0.10000E+03       0.10000E+03         0.0
    8        0.10000E+03       0.10000E+03         0.0
    9        0.10000E+03      -0.10000E+03         0.0
   10       -0.10000E+03      -0.10000E+03         0.0
```

Table III

25-BAR TOWER SAMPLE OUTPUT

AREA/COORDINATE VARIABLES

```
THERE ARE    8  AREA DESIGN VARIABLES

INITIAL VALUES
   0.20000E+01 0.20000E+01 0.20000E+01 0.20000E+01 0.20000E+01 0.20000E+01

LOWER BOUNDS
   0.10000E-04 0.10000E-04 0.10000E-04 0.10000E-04 0.10000E-04 0.10000E-04

UPPER BOUNDS
   0.50000E+02 0.50000E+02 0.50000E+02 0.50000E+02 0.50000E+02 0.50000E+02

THERE ARE    5  COORDINATE VARIABLES

INITIAL VALUES
   0.37500E+02 0.37500E+02 0.10000E+03 0.10000E+03 0.10000E+03

LOWER BOUNDS
   0.10000E+00 0.10000E+00 0.10000E+00 0.10000E+00 0.10000E+00

UPPER BOUNDS
   0.50000E+03 0.50000E+03 0.50000E+03 0.50000E+03 0.50000E+03



JOINT DISPLACEMENT CONSTRAINTS

DIRECTION 1=X, 2=Y, 3=Z, 0=RESULTANT

              LOAD     LOWER        UPPER
 NODE  DIR.   COND.    BOUND        BOUND
   1     1      1   -0.3500E+00   0.3500E+00
   2     1      1   -0.3500E+00   0.3500E+00
   1     2      1   -0.3500E+00   0.3500E+00
   2     2      1   -0.3500E+00   0.3500E+00



FREQUENCY CONSTRAINTS
LOWER BOUNDS IN CPS

FREQUENCY       LOWER
 NUMBER         BOUND
    1         0.1600E+02
```

Table IV

25-BAR TOWER SAMPLE OUTPUT

FINAL OPTIMIZATION INFORMATION

```
FINAL OPTIMIZATION INFORMATION

 OBJ =     0.267256E+03

 DECISION VARIABLES (X-VECTOR)
   1)      0.14595E+01  0.74285E+00  0.98392E+00  0.10425E+01  0.11271E+01  0.73567E+00
   7)      0.85953E+00  0.69571E+00  0.39367E+02  0.46934E+02  0.13895E+03  0.73636E+02
  13)      0.68280E+02

 CONSTRAINT VALUES (G-VECTOR)
   1)     -0.28866E-01 -0.99317E+00 -0.10068E+01 -0.10068E+01 -0.99316E+00 -0.19707E+01
   7)     -0.29252E-01 -0.29252E-01 -0.19707E+01 -0.10160E+01 -0.98405E+00 -0.10063E+01
  13)     -0.10090E+01 -0.99100E+00 -0.10035E+01 -0.71465E+00 -0.12854E+01 -0.53684E+00
  19)     -0.89607E+00 -0.11039E+01 -0.83131E+00 -0.12349E+01 -0.76507E+00 -0.13813E+01
  25)     -0.91932E+00 -0.10807E+01 -0.86905E+00 -0.12349E+01 -0.76507E+00 -0.13813E+01
  31)     -0.10259E+01 -0.97413E+00 -0.10420E+01 -0.71465E+00 -0.12854E+01 -0.53684E+00
  37)     -0.10491E+01 -0.95088E+00 -0.10797E+01 -0.12113E+01 -0.78870E+00 -0.11298E+01
  43)     -0.75447E+00 -0.12455E+01 -0.84920E+00 -0.65536E+00 -0.13446E+01 -0.78832E+00
  49)     -0.11021E+01 -0.89789E+00 -0.10627E+01 -0.65535E+00 -0.13446E+01 -0.78832E+00
  55)     -0.76690E+00 -0.12331E+01 -0.85683E+00 -0.12113E+01 -0.78870E+00 -0.11298E+01
  61)     -0.11145E+01 -0.88546E+00 -0.10703E+01 -0.10478E+01 -0.95216E+00 -0.10412E+01
  67)     -0.10366E+01 -0.96343E+00 -0.10315E+01 -0.10478E+01 -0.95216E+00 -0.10412E+01
  73)     -0.10589E+01 -0.94111E+00 -0.10507E+01 -0.10170E+01 -0.98304E+00 -0.10095E+01
  79)     -0.11018E+01 -0.89817E+00 -0.10570E+01 -0.10170E+01 -0.98304E+00 -0.10095E+01
  85)     -0.92364E+00 -0.10764E+01 -0.95723E+00 -0.11010E+01 -0.89902E+00 -0.14719E+01
  91)     -0.11726E+01 -0.82740E+00 -0.18066E+01 -0.85724E+00 -0.11428E+01 -0.33284E+00
  97)     -0.80677E+00 -0.11932E+01 -0.96989E-01 -0.85724E+00 -0.11428E+01 -0.33284E+00
 103)     -0.11518E+01 -0.84815E+00 -0.17096E+01 -0.11010E+01 -0.89902E+00 -0.14719E+01
 109)     -0.78602E+00 -0.12140E+01 -0.17345E-04 -0.11951E+01 -0.80493E+00 -0.17520E+01
 115)     -0.84000E+00 -0.11600E+01 -0.38325E+00 -0.74877E+00 -0.12512E+01 -0.31550E-01
 121)     -0.81120E+00 -0.11888E+01 -0.27219E+00 -0.74877E+00 -0.12512E+01 -0.31551E-01
 127)     -0.11316E+01 -0.86840E+00 -0.15073E+01 -0.11951E+01 -0.80493E+00 -0.17520E+01
 133)     -0.11028E+01 -0.89721E+00 -0.13962E+01 -0.99416E+00 -0.10058E+01 -0.98209E+00
 139)     -0.12234E+01 -0.77661E+00 -0.16847E+01 -0.90920E+00 -0.10908E+01 -0.72168E+00
 145)     -0.72096E+00 -0.12790E+01 -0.14473E+00 -0.99416E+00 -0.10058E+01 -0.98209E+00
 151)     -0.68067E+00 -0.13193E+01 -0.21237E-01 -0.90919E+00 -0.10908E+01 -0.72158E+00
 157)     -0.11831E+01 -0.81690E+00 -0.15612E+01

 THERE ARE     7 ACTIVE CONSTRAINTS
 CONSTRAINT NUMBERS ARE
     1     7     8   111   120   126   153

 THERE ARE     0 VIOLATED CONSTRAINTS

 THERE ARE     0 ACTIVE SIDE CONSTRAINTS

 TERMINATION CRITERION
     ITER EQUALS ITMAX

 NUMBER OF ITERATIONS =    20

 OBJECTIVE FUNCTION WAS EVALUATED             60   TIMES

 CONSTRAINT FUNCTIONS WERE EVALUATED          60   TIMES

 GRADIENT OF OBJECTIVE WAS CALCULATED         20   TIMES

 GRADIENTS OF CONSTRAINTS WERE CALCULATED     20   TIMES
```

V. USER GUIDE

A. INTRODUCTION

In developing any computer code for engineering analysis, it is necessary to additionally develop concise, easily understood software. This USER GUIDE is writen to be easily followed assuming minimal FORTRAN knowledge. The format follows that of the optimization code, COPES/CONMIN, reference 1.

This chapter is devoted to acquainting the user with the code and necessary input data. A simple 3-bar truss analysis is used as the example.

B. GENERAL FORMULATION

Each data card is set up to show the input data necessary with the 3-bar truss example underneath. Formats are of "I5" and "F10.0" type. "I" formats must be right justified, and "F" formats must have the decimal point. The number of cards read per data block is listed at the bottom of each block.

C. CONSTRAINTS

Constraints are calculated and stored in the G vector as listed in the following chart. The total number of constraints NCON = 2*NDSPLC + NFREQ + NE*NLC. When any of the constraints are missing from the G vector, all constraints are moved up.

For example, if there is no frequency constraint, then a displacement constraint would fill the first location of the G vector.

$$\underset{\sim}{G} = \left\{ \begin{array}{c|ll}
\dfrac{\lambda_1}{\bar{\lambda}_1} - 1 & \text{NFREQ} & \\
\vdots & \text{(FREQUENCY CONSTRAINTS)} & \\
\dfrac{\lambda_i}{\bar{\lambda}_i} - 1 & & \\
\hdashline
\dfrac{u_1}{\bar{u}_1^{-}} - 1 & \text{2* NDSPLC * NLC} & \\
\vdots & \text{(DISPLACEMENT CONSTRAINTS)} & \\
\dfrac{u_n}{\bar{u}_n^{+}} - 1 & & \\
\hdashline
\dfrac{\sigma_{11}}{\bar{\sigma}_1^{-}} - 1 & \text{MEMBER \#1} & \text{STRESS AND} \\
\dfrac{\sigma_{11}}{\bar{\sigma}_1^{-}} - 1 & \text{LC \#1} & \text{BUCKLING} \\
\dfrac{\sigma_{11}}{\bar{\sigma}_1^{E}} - 1 & & \\
\hdashline
\dfrac{\sigma_{21}}{\bar{\sigma}_2^{-}} - 1 & \text{MEMBER \#2} & \text{STRESS AND} \\
\vdots & \text{LC \#1} & \text{BUCKLING} \\
\hdashline
\dfrac{\sigma_{NE}}{\sigma_{NE}^{E}} - 1 & \text{MEMBER \#NE} & \text{STRESS AND} \\
 & \text{LC \quad \#NLC} & \text{BUCKLING}
\end{array} \right.$$

D. EXAMPLE

The initial layout of the 3-bar truss is shown in Figure 6.1. Stress constraints were imposed as well as constraints on Euler buckling, displacement, and first fundamental frequency.

With geometry specified as per the figure, 2 independent load conditions (P1,P2) were imposed with 3 member sizing variables (A1, A2, A3) linked so that A1=X(1), A2=X(2), A3=X(1).

1. Properties/Conditions

The material used had a density (ρ)=0.1 lb/in^3. Young's Modulus was selected as 10^7 psi.

LOADS: P1=P2= 20,000 lbs.

STRESS LIMITS: $-15{,}000 < \sigma_i < 20{,}000$ psi i=1,3

Symmetry was maintained by linking of variables so A1=A3. Initial design began with A1=A2=A3= 1.0 in. One non-structural mass of 500 lbs was attached at joint 2. Displacement constraints were imposed between -.02 and .02 inches in the x-direction with the first natural frequency limited to a value $\omega_n < 20$ Hz.

2. Input Control Parameters

The following input control parameters are given for ease of the following example. NE=3, NJ=4, NCJ=4, NMT=1, NLC=2, NEIG=2, NEIG1=2, NFMASS=1, NEUBC=1, NDSPLC=2, NFREQ=1, LMASS=0, IDVCLC=2. Table V is a listing of commonly used nomenclature.

TABLE V

COMMON VARIABLE NOMENCLATURE

A- MEMBER'S CROSS-SECTIONAL AREA
BL- LOWER BOUND ON DISPLACEMENTS
BU- UPPER BOUND ON DISPLACEMENTS
DIR- DIRECTION 1=X, 2=Y, 3=Z, 0=LIMIT ON RESULTANT DISPL.
E- YOUNGS MODULUS
ELNO- ELEMENT NUMBER
EPSEIG- CONVERGENCE TOLERANCE OF EIGENVALUE SOLUTIONS (DEFAULT=.0001)
FC1,FC2,....FCN- LOWER BOUND ON FIRST,SECOND, ETC. SYSTEM NATURAL FREQUENCY
FX- LOAD FORCES BEING APPLIED IN THE X DIRECTION
FY- LOAD FORCES BEING APPLIED IN THE Y DIRECTION
FZ- LOAD FORCES BEING APPLIED IN THE Z DIRECTION
GRAV- ACCELERATION DUE TO GRAVITY (DEFAULT= 386.4)
IX- CONSTRAINT IDENTIFIER. IF NON-ZERO THE X-DOF IS CONSTRAINED
IY- CONSTRAINT IDENTIFIER. IF NON-ZERO THE Y-DOF IS CONSTRAINED
IZ- CONSTRAINT IDENTIFIER. IF NON-ZERO THE Z-DOF IS CONSTRAINED
JN- JOINT NUMBER (GLOBAL)
KEULER- EULER BUCKLING COEFFICIENT FOR BAR ELEMENTS
LC- LOAD CONDITION
LMASS- LUMPED MASS OPTIONS. IF LMASS .NE. 0 LUMPED MASS MATRIX USED
IF LMASS =0 CONSISTENT MASS MATRIX USED
NEIG1-NUMBER OF EIGENVALUE/EIGENVECTOR TO BE EVALUATED DEFAULT =MIN(2*NEIG, NEIG+8)
NEUBC- BUCKLING CONSTRAINT IDENTIFIERS . IF NEUBC. NE.0 EULER BUCKLING WILL BE IMPOSED IN BAR ELEMENTS
NFMASS-NUMBER OF FIXED MASSES ATTACHED TO THE STRUCTURE
NFREQ-NUMBER OF FREQUENCY CONSTRAINTS
NID- NUMBER OF INDEPENDENT DEGREES OF FREEDOM
NJ-NUMBER OF JOINTS
NLC- NUMBER OF LOADING CONDTIONS
NLJ- NUMBER OF LOADED JOINTS FOR THIS LOAD CONDITION
NMT- NUMBER OF SEPARATE MATERIAL TYPES
RHO- MATERIAL DENSITY
SIGMIN- MINIMUM ALLOWABLE STRESS
SIGMAX- MAXIMUM ALLOWABLE STRESS
XA- INITIAL VALUE OF AREA DESIGN VARIABLE
XAL- LOWER BOUND
XAU- UPPER BOUND
XC- INITIAL VALUE OF COORDINATE DESIGN VARIABLE
XCL- LOWER BOUNDS
XCU- UPPER BOUNDS

The following user's manual is divided into blocks A through M. Appearing directly below each data field line are the parameters for the 3-bar truss example. It is important to note the user may choose any units; however, all units must remain consistent throughout the problem.

DATA BLOCK A

DESCRIPTION: Title Card

Format and Example

TITLE	FORMAT 20A4

3-BAR TRUSS (EXAMPLE)

FIELD	CONTENTS
1	ANY 80 CHARACTER TITLE MAY BE GIVEN ON THIS LINE

DATA BLOCK B

DESCRIPTION: Control Parameters

Format and Example

NE	NJ	NCJ	NMT	NLC	NEUBC	NDSPLC	NPRI	FORMAT
								8I5
3	4	4	1	2	1	2	0	

NEIG	NEIG1	NFMASS	NFREQ	IDVCLC	IRECP	FORMAT
2	2	1	1	2	0	5I5

NOTE: DEFINITIONS OF INPUT CONTROL PARAMETERS FOR PROGRAM NEXT PAGE.

FIELD	CONTENT
1	NE-number of elements
2	NJ-number of joints
3	NCJ-number of constrained joints
4	NMT-number of seperate material types
5	NLC-number of load conditions
6	NEUBC-buckling constraint identifier (If NEUBC.NE.0 -EULER buckling constraints will be imposed on bar ele.)
7	NDSPLC-number of displacement constraints
8	NPR1-input print control (if NPR1.ne.0 input information will not be printed)
1	NEIG-number of precise eigenvalues to be evaluated
2	NEIG1-number of eigenvalues to be evaluated DEFAULT=min. of (2*NEIG , NNEIG+8)
3	NFMASS-number of fixed masses attached to structure
4	NFREQ-number of frequency constraints

5	IDVCLC-design variable control parameter
	If (IDVCLC.EQ.1) NDV=NDVAR1
	If (IDVCLC.EQ.2) NDV=NDVAR1+ NDVAR2
	If (IDVCLC.EQ.3) NDV=NDVAR2

6	IRECP-recripocal variable identifier If (IRECP.GT.0) the X-vector contains the recripocal of area and VLB & VUB are changed accordingly

DATA BLOCK C

DESCRIPTION: Dynamic Analysis Information

Format and Example

LMASS	GRAV	EPSEIG		FORMAT I5, 2F10.0
0	386.4	0.		

FIELD	CONTENTS
1	LMASS-lumped mass option (if LMASS.NE.0) the lumped mass matrix is used.
2	GRAV-accleration due to gravity (default=386.4 inches/sec)
3	EPSEIG-convergence tolerance on eigenvalue solution. (default=.0001)

DATA BLOCK D

DESCRIPTION: Joint Coordinates &
Design Variable Linking

Format and Example

JN	X	Y	Z	IX	IY	IZ	PCX	PCY	PCZ	FORMAT
										I5, 3F10.0, 3I5, 3F10.0
1	-10.	0.	0.	1	0	0	-1.	0.	0.	
2	0.	-10.	0.	0	0	0	0.	0.	0.	
3	0.	0.	0.	0	0	0	0.	0.	0.	
4	10.	0.	0.	1	0	0	1.	0.	0.	

FIELD	CONTENTS
1	JN-joint coordinate number
2	X-x coordinate
3	Y-y coordinate
4	Z-z coordinate
5	IX-design variable associated with x coord.
6	IY-design variable associated with y coord.
7	IZ-design variable associated with z coord.
8	PCX-participation coefficient of x-coord.
9	PCY-participation coefficient of y-coord.
10	PCZ-participation coefficient of z-coord.

NOTE: Number of cards read=NJ

DATA BLOCK E

DESCRIPTION: Material Properties

Format and Example

E	RHO	SIGMIN	SIGMAX	KEULER	FORMAT 5F10.0
1000000.	.1	-15000.	20000.	4.	

FIELD	CONTENTS
1	E-Young's Modulus
2	RHO-material density
3	SIGMIN-minimum allowable stress
4	SIGMAX-maximum allowable stress
5	KEULER-Euler buckling coefficient for bar element

NOTE: Number of cards read=NMT

DATA BLOCK F

DESCRIPTION: Bar Element Information

Format and Example

ELNO	NODE1	NODE2	MATCOD	NDSG	A	FORMAT 5I5,F10.0
1	1	2	1	1	1.	
2	3	2	1	2	1.	
3	4	2	1	1	1.	

FIELD	CONTENTS
1	ELNO-element number
2	NODE1-global number associated with element node
3	NODE2-global number associated with element node
4	MATCOD-material type of this element
5	NDSG-design variable number associated with this element
6	A-member cross-sectional area

NOTE: Number of cards read=NE

DATA BLOCK G

DESCRIPTION: Joint Constraint Information

Format and Example

JN	IX	IY	IZ		FORMAT 4I5

1	1	1	1	
2	0	0	1	
3	1	1	1	
4	1	1	1	

FIELD	CONTENTS
1	JN-joint number
2	IX x,y,z constraint identifier. (if non-
3	IY zero the corresponding degree of freedom
4	IZ is constrained)

NOTE: Number of cards read=NCJ

DATA BLOCK H

OMIT this card if NLC=0 was read in block B.

DESCRIPTION: Joint Loading Information

Format and Example

NLJ		FORMAT I5
1		
1		

JN	FX	FY	FZ		FORMAT I5,3F10.0
2	14140.	-14140.	0.		
2	-14140.	-14140.	0.		

FIELD	CONTENT
1	NLJ-number of loaded joints for this load condition
1	JN-joint number
2	FX
3	FY- Forces in the X,Y,Z directions
4	FZ

DATA BLOCK I

OMIT this block if NFMASS=0 was read in block B.

DESCRIPTION: Lumped Mass Information

Format and Example

JN	MASS		FORMAT I5,F10.0

2	500.	

FIELD	CONTENTS
1	JN-joint number
2	MASS-concentrated mass at joint (JN) mass is in force units

DATA BLOCK J

OMIT this block if NDVAR1=0

DESCRIPTION: Design Variable Information
(AREA Variables)

Format and Example

XA(I)				FORMAT 8F10.0
1.	1.			
.01	.01			XAL(I)
10.	10.			XAU(I)

FIELD	CONTENTS
1	XA-initial value of area design variables
2	XAL-lower bounds on area design variables
3	XAU-upper bounds on area design variables

NOTE: read one value of XA, XAL, XAU for each independent area variable defined in Block D

Number of cards read =as required

DATA BLOCK K

OMIT this block if NDVAR2=0

DESCRIPTION: Design Variable Information
(COORDINATE Variables)

Format and Example

XC(1)	XC(2)	. . . .	XC(NDVAR1)	FORMAT 8F10.0
10.				
1.0				XCL
20.				XCU

FIELD	CONTENTS
1	XC-initial value of coord. design variables
2	XCL-lower bounds on coord. design variables
3	XCU-upper bounds on coord. design variables

NOTE: read one value of XC, XCL, XCU for each independent coordinate variable defined in Block D

Number of cards read =as required.

DATA BLOCK L

OMIT this block if NDSPLC=0 in Block A

DESCRIPTION: Joint Displacement Constraint Information

Format and Example

JN	DIR	LC	BL	BU		FORMAT 3I5,2F10.0
2	1	1	-.02	.02		
2	2	1	-.02	.02		

FIELD	CONTENTS
1	JN-joint number
2	DIR-direction 1=X 2=Y 3=z 0=limit on resultant displ.
3	LC-load condition
4	BL-lower bound on displacement (If DIR=0 read 0 here)
5	BU-upper bound on displacement

Number of cards read= NDSPLC

DATA BLOCK M

OMIT this block if NFREQ=0 was read in Block A

DESCRIPTION: Frequency Constraint Information

Format and Example

FC1	FC2	FC3	....	.FCN		FORMAT 8F10.0

20.					

FIELD	CONTENTS
1	FC1- lower bound on first natural frequency constraint in CPS. (cycles per second)
N	FCN- lower bound on NFREQ-th natural frequency constraint in CPS. (cycles per second)

NOTE: OMIT this block if NFREQ=0 was read in data block B.

Number of cards read= as required

VI. NUMERICAL EXAMPLES

A. INTRODUCTION

Design of planar trusses and 3-dimensional space towers are presented here and the corresponding numerical results are summarized to demonstrate the use of the code.

In the examples given here, the design variables are member cross-sectional areas and joint coordinates. It should be emphasized that in practical design, the reciprocal of the member areas is usually a better choice for the design variables. However, the purpose here is to knowingly create difficult optimization problems, thus the choice of variables.

The examples begin with the 3-bar truss.

B. CASE 1: 3-BAR PLANAR TRUSS

The simple 3-bar planar truss, as shown in Figure 6.1 has been previously used for the user guide example. This structure was designed for optimum geometry subject to a set of two load conditions, buckling constraints, displacement constraints, and a lower bound on the system's first natural frequency. The allowable stresses specified are

$$-15000. < \sigma_i < 20000. \text{ psi} \qquad i=1,3$$

The member areas were linked in the following groups: A1=A3; A2.

1. Case 1a

Only the stress constraint was imposed for this case. Final design information is given in Table VI. The number of analysis for this design was 38.

2. Case 1b

This case includes the previous constraint plus constraints on buckling (KEULER=4.0), displacement (-.02 -.02 in.), and first natural frequency (ω_n=20.0). Results are given in Table VII. The number of analysis required for this design was 16 with 1.73 seconds of CPU time.

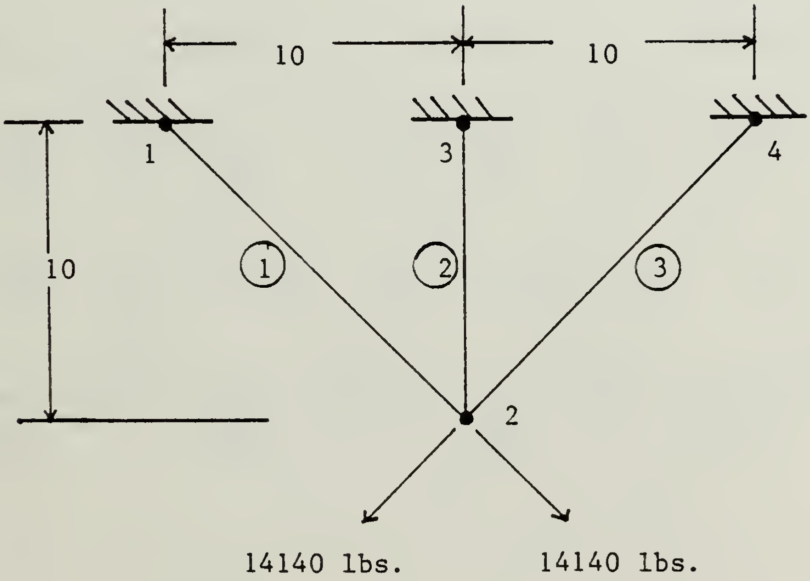


Figure 6.1 3-BAR TRUSS

C. CASE 2: 18-BAR PLANAR TRUSS

A cantiliver truss, as shown in Figure 6.2, has been previously used as a standard test case for structural design [Ref. 2]. The structure was analyzed for a single set of load conditions with allowable stresses being

$$-20000. < \sigma_i < 20000. \text{ psi} \qquad i=1,18$$

Young's modulus was taken as 10^7 psi with a material density $\rho=0.1$ lb./cu in.

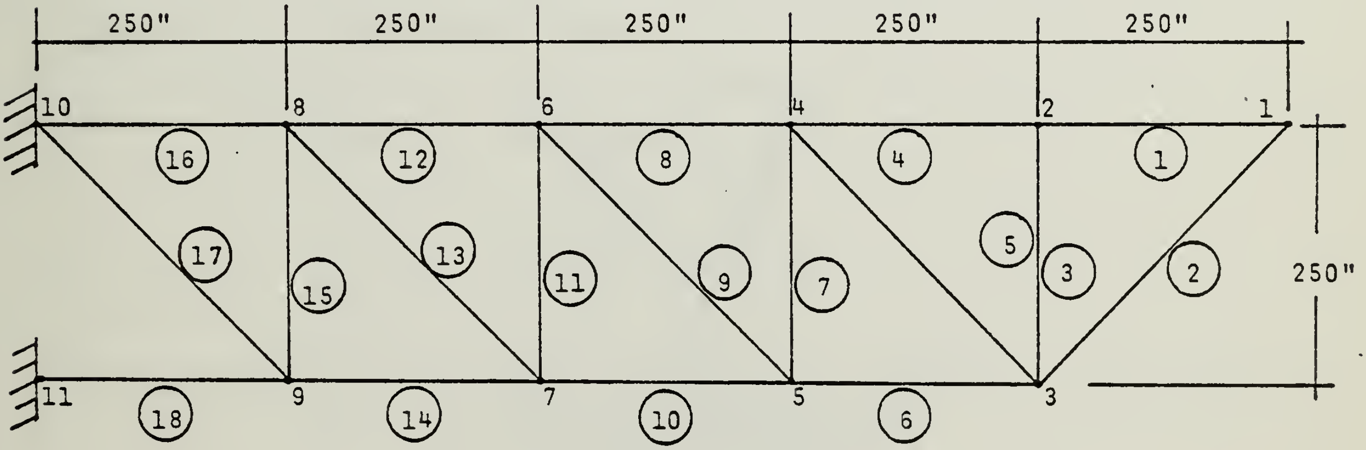


Figure 6.2 18-BAR TRUSS

The independent coordinate variables were taken as X3, Y3, X5, Y5, X7, Y7, X9, Y9. The member areas were linked as follows: A1=A4=A8=A12=A16; A2=A6=A10=A14=A18; A3=A7=A11=A15; A5=A9=A13=A17. There are a total of four independent area variables and eight coordinate variables.

1. Case 2a

This design analysis includes stress, buckling (KEULER=4.0), displacement (-10.0 to 10.0 in.), and a first fundamental frequency of 3 Hz. Additionally, a nonstructural mass of W=5000 lbs. was attached to node 1. The number of analyses for this design was 62. Results are presented in Table VIII. 26.72 seconds of CPU time were used for this calculation.

D. CASE 3: 25-BAR SPACE TOWER

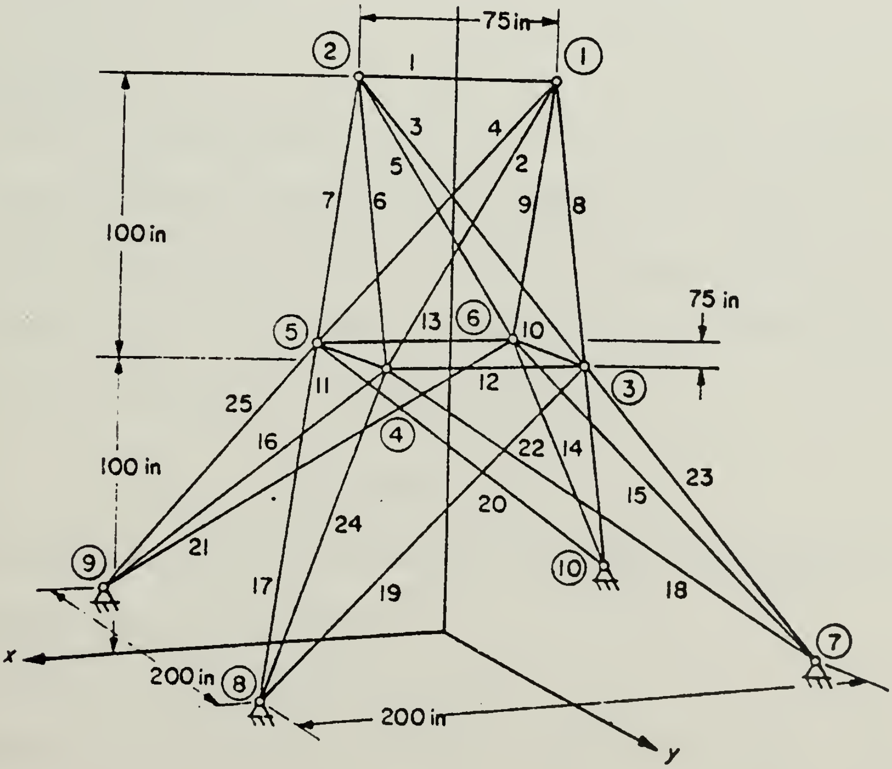


Figure 6.3 25-BAR SPACE TOWER

The 25-bar space tower shown in Figure 6.3 was designed for two independent load conditions given in Table X. The allowable stresses were specified as follows

$$-40000. < \sigma_i < 40000. \text{ psi} \qquad i=1,25$$

Young's modulus was selected as 10^7 psi with a material density ρ=.1 lb/cu. in. Members are assumed tubular with a nominal diameter to thickness ratio of D/t=100 giving KEULER=39.274. Symmetry was imposed in both the x-z and y-z planes. Non-structural masses of W=500 lbs. were attached at nodes 1 and 2. Coordinate variables were X4, Y4, Z4, X8, and Y8 with the remaining coordinates linked to maintain symmetry. Area variables were linked in the following manner: A1; A2=A3=A4=A5; A6=A7=A8=A9; A10=A11; A12=A13; A14=A15=A16=A17; A18=A19=A20=A21; A22=A23=A24=A25.

1. Case 3a

Stress, displacement (-0.35 to 0.35 in.), Euler buckling and first natural frequency limited to a value $\omega_n > 16$ Hz. were imposed for this case. Final design information is given in Table XI. The number of analyses for this design was 61 with 27.99 seconds of CPU time used.

E. CASE 4: 234-BAR SPACE TOWER

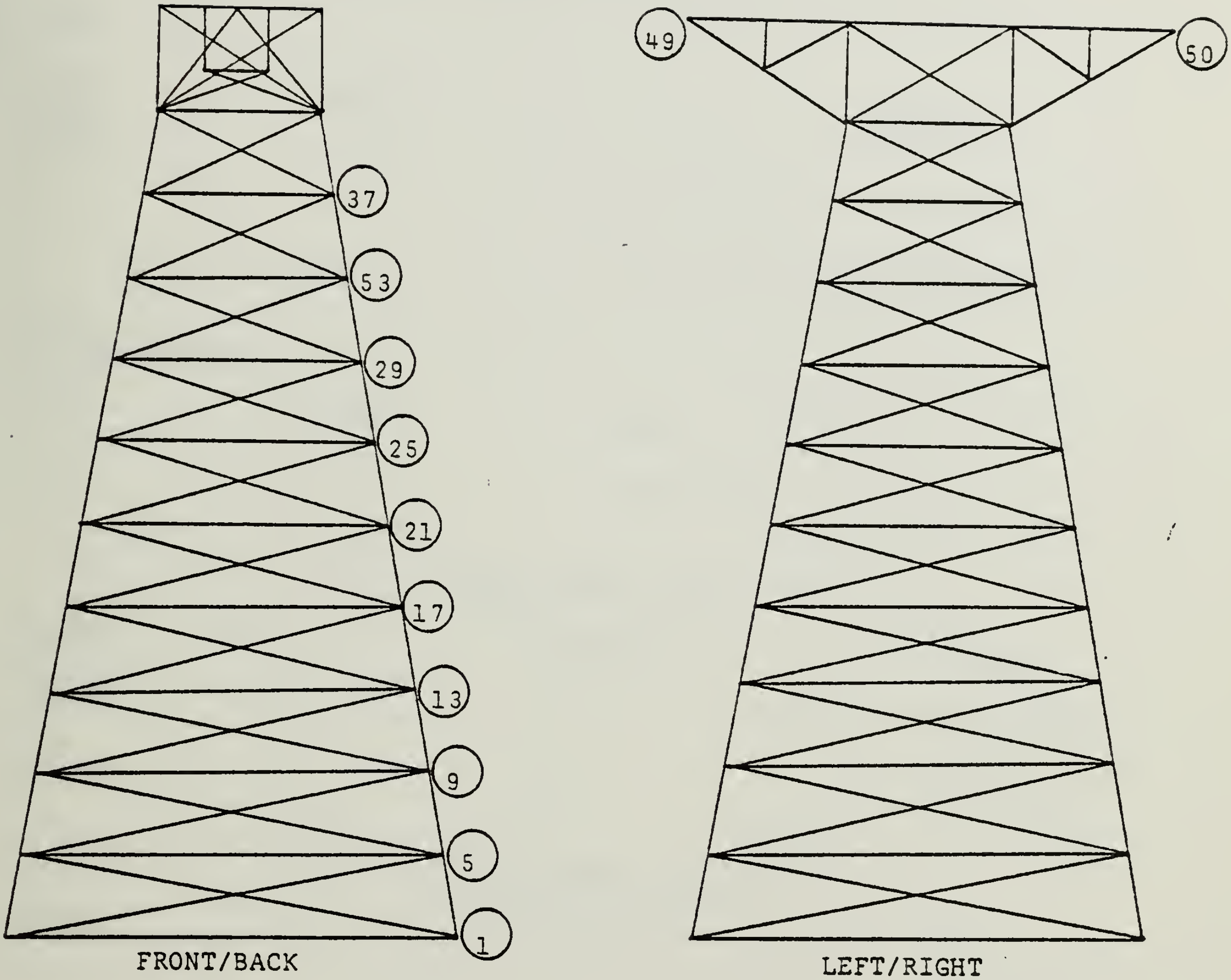
The inital layout of the tower is shown in Figure 6.4 stress limits were as follows

$$-15000. < \sigma_i < 20000. \text{ psi} \qquad i=1,234$$

Young's modulus was chosen as steel $3.\text{x}10^7$ psi with a material density of aluminum ρ =.1 lbs/cu. in.

1. Case 4a

Stress constraints as well as constraints on Euler buckling were imposed. The resulting problem had 56 area design variables and 42 coordinate variables. This problem required 91 structural analyses using 72 minutes of CPU time. The objective function was evaluated 89 times and gradients were calculated 30 times. Results are presented in Tables XII through XIV. Although the weight of the structure was only reduced by 2%, it should be noted that constraints were initially violated and the optimizer overcame the constraint violations. It is believed the optimum that was reached is not the true optimum because of the extreme non-linearity of the problem.



FRONT/BACK

LEFT/RIGHT

Figure 6.4 234-BAR SPACE TOWER

Table VI

3-BAR TRUSS. DESIGN INFORMATION (STRESS)

BODY

LOAD COND.	JOINT	LOADS		
		X	Y	Z
1	2	0.1414E+05	-0.1414E+05	0.0
2	2	-0.1414E+05	-0.1414E+05	0.0

FIXED MASSES

NO.	JOINT	MASS
1	2	500 lbs.

AREA (sq. in.)

MEMBER	INITIAL	FINAL
A1=A3	1.0	.7662E+00
A2	1.0	.4833E+00

COORDINATES (in.)

JOINT	INITIAL	FINAL
2	10	.9856E+01

FINAL WEIGHT FOR AREA AND COORDINATES

WEIGHT = 2.6349 (lbs.)

Table VII

3-BAR TRUSS. DESIGN INFORMATION
(STRESS, DISPLACEMENT, BUCKLING, FREQUENCY)

BODY

JOINT LOADING INFORMATION

SAME AS TABLE VI

JOINT DISPLACEMENT INFORMATION

JOINT NUMBER	DIR.	LOAD COND.	LOWER BOUND	UPPER BOUND
2	1	1	-.02	.02
2	2	1	-.02	.02

AREA (sq. in.)

MEMBER	INITIAL	FINAL
A1=A3	1.0	0.99995E+00
A2	1.0	0.1000 E-01

COORDINATES (in.)

JOINT	INITIAL	FINAL
2	10.0	0.99986E+01

FINAL WEIGHT = 2.8381 (lbs.)

CRITICAL CONSTRAINT - FREQUENCY

Table VIII

18-BAR TRUSS. LOAD CONDITIONS

BODY

LOAD CONDITIONS (lbs.)

LOAD COND.	JOINT	LOADS X	 Y	 Z
1	1	0.0	-0.2000E+05	0.0
1	2	0.0	-0.2000E+05	0.0
1	4	0.0	-0.2000E+05	0.0
1	6	0.0	-0.2000E+05	0.0
1	8	0.0	-0.2000E+05	0.0

FIXED MASS INFORMATION

NO.	JOINT	MASS
1	1	5000 (lbs.)

Table IX

18-BAR TRUSS. DESIGN INFORMATION
(STRESS, DISPLACEMENT, EULER BUCKLING, FREQUENCY)

AREA (sq. in.)

MEMBER	INITIAL	FINAL
A1=A4=A8=A12=A16	10.0	38.20
A2=A6=A10=A14=A18	10.0	38.27
A3=A7=A11=A15	10.0	15.98
A4=A9=A13=A17	10.0	20.62

COORDINATES (in.)

JOINT	INITIAL		FINAL	
	X	Y	X	Y
3	1000.	0.	859.	0.
5	750.	0.	628.	0.
7	500.	0.	384.	0.
9	250.	0.	148.	0.

FINAL WEIGHT = 13,940 (lbs.)

CRITICAL CONSTRAINT - FREQUENCY

Table X

25-BAR TRUSS. LOAD CONDITIONS

BODY

LOAD CONDITIONS (lbs.)

LOAD COND.	JOINT	LOADS X	 Y	 Z
1	1	0.0	2000.	-5000.
	2	0.0	-2000.	-5000.
2	1	1000.	10000.	-5000.
	2	0.	10000.	-5000.
	3	500.	0.	0.
	6	500.	0.	0.

FIXED MASS INFORMATION

NO.	JOINT	MASS
2	1	500.(lbs.)
	2	500.(lbs.)

Table XI

25-BAR TRUSS. DESIGN INFORMATION (STRESS, DISPLACEMENT, EULER BUCKLING, FREQUENCY)

AREA (sq. in.)

MEMBER	INITIAL	FINAL
A1	2.0	1.46
A2=A3=A4=A5	2.0	0.74
A6=A7=A8=A9	2.0	0.98
A10=A11	2.0	1.04
A12=A13	2.0	1.12
A14=A15=A16=A17	2.0	0.74
A18=A19=A20=A21	2.0	0.86
A22=A23=A24=A25	2.0	0.70

COORDINATES (in.)

JOINT	INITIAL			FINAL		
	X	Y	Z	X	Y	Z
4	37.5	37.5	100	39.4	46.9	138.9
8	100.0	100.0	0.0	73.6	68.3	0.0

FINAL WEIGHT = 267 (lbs.)

CRITICAL CONSTRAINT - FREQUENCY

Table XII

234-BAR SPACE TOWER. LOADING INFORMATION

BODY

LOAD CONDITIONS (lbs.)

LOAD COND.	JOINT	LOADS X	LOADS Y	LOADS Z
1	49	6000.	-20000.	0.0
1	50	6000.	-20000.	0.0
2	49	6000.	-20000.	0.0
2	50	-6000.	-20000.	0.0
3	49	6000.	-20000.	0.0
3	50	3000.	-10000.	5000.
4	49	3000.	-10000.	-5000.
4	50	3000.	-10000.	5000.
5	49	-3000.	10000.	5000.
5	50	-3000.	10000.	-5000.

FIXED MASS INFORMATION

NO.	JOINT	MASS
1	49	200.(lbs.)
2	50	200.(lbs.)

Table XIII

234-BAR SPACE TOWER. DESIGN INFORMATION

	AREA (sq. in.)	
MEMBER	INITIAL	FINAL
A1,A2,A3,A4	25.0	25.38
A5,A6,A7,A8	25.0	25.35
A9,A10,A11,A12	25.0	25.28
Ak3,A14,A15,A16	25.0	25.21
A17,A18,A19,A20	25.0	25.14
A21,A22,A23,A24	25.0	25.07
A25,A26,A27,A28	25.0	25.00
A29,A30,A31,A32	25.0	24.95
A33,A34,A35,A36	25.0	24.89
A37,A38,A39,A40	25.0	24.85
A41,A42,A43,A44	25.0	24.98
A45,A46,A47,A48	25.0	24.87
A49,A50,A51,A52	25.0	24.88
A53,A54,A55,A56	25.0	24.89
A57,A58,A59,A60	25.0	24.89
A61,A62,A63,A64	25.0	24.90
A65,A66,A67,A68	25.0	24.91
A69,A70,A71,A72	25.0	24.91
A73,A74,A75,A76	25.0	24.91
A77,A78,A79,A80	25.0	24.91
A81,A83	25.0	24.96
A82,A84	25.0	24.96
A85,A87	25.0	24.96
A86,A88	25.0	24.95
A89,A90,A91,A92,A93,A94,A95,A96	25.0	24.68
A97,A98,A99,A100,A101,A102,A103,A104	25.0	24.69
A150,A106,A107,A108,A109,A110,A111,A112	25.0	24.71
A113,A114,A115,A116,A117,A118,A119,A120	25.0	24.73
A121,A122,A123,A124,A125,A126,A127,A128	25.0	24.74
A129,A130,A131,A132,A133,A134,A135,A136	25.0	24.75
A137,A138,A139,A140,A141,A142,A143,A144	25.0	24.74
A145,A146,A147,A148,A149,A150,A151,A152	25.0	24.72
A153,A154,A155,A156,A157,A158,A159,A160	25.0	24.69
A161,A162,A163,A164,A165,A166,A167,A168	25.0	24.65
A169,A170,A171,A172,A173,A174,A175,A176	25.0	24.82
A177,A178,A179,A180	25.0	24.96
A181,A182,A183,A184	25.0	24.96
A185,A186,A187,A188	25.0	24.87
A189,A190,A191,A192	25.0	24.86

Table XIII (cont'd)

AREA (sq. in.)

MEMBER	INITIAL	FINAL
A193,A194,A195,A196	25.0	24.95
A197,A198,A199,A200	25.0	24.97
A201,A202	25.0	24.91
A203,A204	25.0	24.92
A205,A206,A207,A208	25.0	24.86
A209,A210,A211,A212	25.0	24.87
A213,A214	25.0	24.89
A215,A216	25.0	24.90
A217,A218	25.0	24.91
A219,A220	25.0	24.92
A221,A222	25.0	24.92
A223,A224	25.0	24.93
A225,A226	25.0	24.93
A227,A228	25.0	24.94
A229,A230	25.0	24.94
A231,A232	25.0	24.94
A233,A234	25.0	24.93

COORDINATES (in.)

JOINT		INITIAL			FINAL	
	X	Y	Z	X	Y	Z
1	120	0*	120	120.5	0	121.4
5	111	120	111	110.7	120.4	112.1
9	102	240	102	102.2	241.2	103.2
13	93	360	93	93.1	362.6	93.7
17	84	480	84	84.0	483.8	84.4
21	75	600	75	74.9	604.5	75.2
25	66	720	66	65.9	724.2	65.9
29	57	840	57	56.8	842.6	56.8
33	48	960	48	47.8	960.4	47.8

Initial weight = 84,524 lbs. Final weight = 83,142 lbs.

*Final weight (AREA VARBIABLES ONLY) = 28,900 lbs.
* This clearly indicates optimum not reached with previous case.

Table XIII (cont'd)

COORDINATES (in.)

JOINT	INITIAL			FINAL		
	X	Y	Z	X	Y	Z
37	39	1080	39	38.8	1077.4	38.8
41	30	0*	30	29.9	-	29.9
45	30	1248	30	29.8	1212.0	29.9
49	0*	1248	90	-	1203.5	90.0
51	15	1224	60	15.0	1194.1	58.9
53	15	1248	60	15.0	1214.7	59.2

*NOT A DESIGN VARIABLE

VII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The finite element code was presented coupled to an optimizer for truss analysis and design. Trusses were designed for minimum weight with multiple load conditions considered.

The displacement method for static analysis and the subspace iteration method for eigenvalues were applied.

Several examples were considered. In every case the code worked as an analysis tool, and significant weight reductions were obtained with the coupled optimizer CONMIN. Run times and results compared to the same test cases with other codes indiate that the code is competitive as a design tool.

B. RECOMMENDATIONS

The following recommendations may be of value for follow on work:

1. The code should be modified so the user can access stresses directly.
2. The code should be extended to include other elements such as frames and plates.
3. An out of core equation solver should be added.
4. The method of gradient calculation should be dependent on specific gradients required reference 3 and reference 4.

5. Gradients of frequency constraints would benefit from a more efficient algorithm reference 5.

6. The need for a large scale public structural optimization code still exists.

APPENDIX A

DATA FILES

A. INTRODUCTION

This appendix contains the data files used to create the test cases in Chapter VI. Additionally the data file for the user's guide in complete form is presented.

Table XIV

DATA FILE 3-BAR TRUSS

(STRESS)

```
3- BAR TRUSS (TEST CASE A-STRESS ONLY)
    3    4    4    1    2    0    0    0
    0    0    1    0    2
    0    386.4     0.0
    1  -10.        0.       0.          1    0    0    -1.
    2    0.      -10.       0.          0    0    0     0
    3    0.        0.       0.          0    0    0     0.
    4   10.        0.       0.          1    0    0     1.
 10000000.   .1      -15000.  20000.    4.
    1    1    2    1    1    1.
    2    3    2    1    2    1.
    3    4    2    1    1    1.
    1    1    1    1
    2    0    0    1
    3    1    1    1
    4    1    1    1
    1
    2  14140.  -14140.    0.
    1
    2 -14140.  -14140.    0.
    2    500.
 1.        1.
 .01       .01
 10.        10.
 10.
 1.0
 20.
```

Table XV

DATA FILE 3-BAR TRUSS

(STRESS, DISPLACEMENT, BUCKLING, FREQUENCY)

```
3- BAR TRUSS (TEST CASE D-STRESS,DISPL.,BUCKL.,FREQ. )
   3    4    4    1    2    1    2    0
   2    2    1    1    2
   0     386.4      0.0
   1  -10.          0.        0.        1    0    0    -1.
   2    0.       -10.         0.        0    0    0     0
   3    0.          0.        0.        0    0    0     0.
   4   10.          0.        0.        1    0    0     1.
 10000000.    .1      -15000.  20000.    4.
   1    1    2    1    1    1.
   2    3    2    1    2    1.
   3    4    2    1    1    1.
   1    1    1    1
   2    0    0    1
   3    1    1    1
   4    1    1    1
   1
   2  14140.  -14140.    0.
   1
   2 -14140.  -14140.    0.
   2     500.
 1.        1.
 .01       .01
 10.        10.
 10.
 1.0
 20.
   2    1    1    -.02        .02
   2    2    1    -.02        .02
20.
```

Table XVI

DATA FILE 18-BAR TRUSS

(STRESS, DISPLACEMENT, BUCKLING, FREQUENCY)

```
 18-BAR TRUSS CASE (TEST CASE STRESS/DISP./BUCKLING/FREQ.)
  18   11   11    1    1    1    1    0
   2    4    1    1    2
   0    386.4     0.
   1 1250.    250.
   2 1000.    250.
   3 1000.                             1    2    0 1.       1.
   4 750.     250.
   5 750.     0.                       3    4    0 1.       1.
   6 500.     250.
   7 500.     0.                       5    6      1.       1.
   8 250.     250.
   9 250.     0.                       7    8      1.       1.
  10 0.       250.
  11
10000000. .1         -20000.   20000.    4.
   1    1    2    1    1 10.
   2    1    3    1    2 10.
   3    2    3    1    3 10.
   4    2    4    1    1 10.
   5    3    4    1    4 10.
   6    3    5    1    2 10.
   7    4    5    1    3 10.
   8    4    6    1    1 10.
   9    5    6    1    4 10.
  10    5    7    1    2 10.
  11    6    7    1    3 10.
  12    6    8    1    1 10.
  13    7    8    1    4 10.
  14    7    9    1    2 10.
  15    8    9    1    3 10.
  16    8   10    1    1 10.
  17    9   10    1    4 10.
  18    9   11    1    2 10.
   1    0    0    1
   2              1
   3              1
   4              1
   5              1
   6              1
   7              1
   8              1
   9              1
  10    1    1    1
  11    1    1    1
   5
   1          -20000.
   2          -20000.
   4          -20000.
   6          -20000.
   8          -20000.
   1  5000.
30.       30.       30.       30.
1.        1.        1.        1.
1000.     1000.     1000.     1000.
1000.     0.        750.      0.        500.      0.        250.      0.
700.      -50.      500.      -50.      200.      -50.      50.       -100.
1200.     200.      1000.     150.      750.      150.      500.      150.
   1    2    1   -10.      10.
4.0
```

Table XVII

DATA FILE 25-BAR SPACE TOWER

(STRESS, DISPLACEMENT, BUCKLING, FREQUENCY)

```
25-BAR SPACE TRUSS (TEST CASE STRESS/DISP./BUCKLING/FREQ.)
  25   10   10    1    2    1    4    0
   2    2    2    1    2
   0   386.4      0.
   1  -37.5       0.0       200.     0    0    0    0        0     0.
   2   37.5       0.0       200.     0    0    0
   3   -37.5      37.5      100.     1    2    3   -1.       1.    1.
   4   37.5       37.5      100.     1    2    3    1.       1.    1.
   5   37.5       -37.5     100.     1    2    3    1.      -1.    1.
   6  -37.5      -37.5      100.     1    2    3   -1.      -1.    1.
   7   -100.      100.      0.       4    5    0   -1.       1.    0.
   8   100.       100.      0.       4    5    0    1.       1.
   9   100       -100.      0.       4    5    0    1.      -1.
  10   -100.     -100.      0.       4    5    0   -1.      -1.
 10000000.    .1     -40000.     40000.     39.274
   1    1    2    1    1    2.
   2    1    4    1    2    2.
   3    2    3    1    2    2.
   4    1    5    1    2    2.
   5    2    6    1    2    2.
   6    2    4    1    3    2.
   7    2    5    1    3    2.
   8    1    3    1    3    2.
   9    1    6    1    3    2.
  10    3    6    1    4    2.
  11    4    5    1    4    2.
  12    4    3    1    5    2.
  13    5    6    1    5    2.
  14    3   10    1    6    2.
  15    6    7    1    6    2.
  16    9    4    1    6    2.
  17    8    5    1    6    2.
  18    7    4    1    7    2.
  19    8    3    1    7    2.
  20   10    5    1    7    2.
  21    9    6    1    7    2.
  22   10    6    1    8    2.
  23    7    3    1    8    2.
  24    8    4    1    8    2.
  25    9    5    1    8    2.
   1
   2
   3
   4
   5
   6
   7    1    1    1
   8    1    1    1
   9    1    1    1
  10    1    1    1
   2
   1    0.    20000.     -5000.
   2    0.   -20000.     -5000.
   4
   1    1000.    10000.    -5000.
   2    0.       10000.    -5000.
   3    500.      0.        0.
   6    500.      0.        0.
   1    500.
   2    500.
   2.            2.           2.           2.           2.           2.           2.           2.
 0.00001     0.00001     0.00001     0.00001     0.00001     0.00001     0.00001     0.00001
   50.          50.          50.          50.          50.          50.          50.          50.
   37.5         37.5         100.         100.         100.
   .1           .1           .1           .1           .1
   500.         500.         500.         500.         500.
   1    1    1    -.35        .35
   2    1    1    -.35        .35
   1    2    1    -.35        .35
   2    2    1    -.35        .35
16.0
```

Table XVIII

DATA FILE 234-BAR SPACE TOWER

```
234-BAR SPACE TOWER DESIGN (TEST CASE STRESS,BUCK.,DISPL.,FREQ.)
  234   58    4    1    5    1   20     0
    1    3    2    1    2
    0    386.4     0.
    1    120.      0.        120.      1    0    2    1.        0.    1.
    2   -120.      0.         120.     1    0    2   -1.        0.    1.
    3    -120.     0.0       -120.     1    0    2    -1.       0.   -1.
    4     120.     0.       -120.      1    0    2     1.       0.   -1.
    5    111.      120.      111.      3    4    5    1.        1.    1.
    6   -111.      120.       111.     3    4    5   -1.        1.    1.
    7    -111.     120.      -111.     3    4    5    -1.       1.   -1.
    8     111.     120.     -111.      3    4    5     1.       1.   -1.
    9    102.      240.      102.      6    7    8    1.        1.    1.
   10   -102.      240.       102.     6    7    8   -1.        1.    1.
   11    -102.     240.      -102.     6    7    8    -1.       1.   -1.
   12     102.     240.     -102.      6    7    8     1.       1.   -1.
   13    93.       360.      93.       9   10   11    1.        1.    1.
   14   -93.       360.       93.      9   10   11   -1.        1.    1.
   15    -93.      360.      -93.      9   10   11    -1.       1.   -1.
   16     93.      360.     -93.       9   10   11     1.       1.   -1.
   17    84.       480.      84.      12   13   14    1.        1.    1.
   18   -84.       480.       84.     12   13   14   -1.        1.    1.
   19    -84.      480.      -84.     12   13   14    -1.       1.   -1.
   20     84.      480.     -84.      12   13   14     1.       1.   -1.
   21    75.       600.      75.      15   16   17    1.        1.    1.
   22   -75.       600.       75.     15   16   17   -1.        1.    1.
   23    -75.      600.      -75.     15   16   17    -1.       1.   -1.
   24     75.      600.     -75.      15   16   17     1.       1.   -1.
   25    66.       720.      66.      18   19   20    1.        1.    1.
   26   -66.       720.       66.     18   19   20   -1.        1.    1.
   27    -66.      720.      -66.     18   19   20    -1.       1.   -1.
   28     66.      720.     -66.      18   19   20     1.       1.   -1.
   29    57.       840.      57.      21   22   23    1.        1.    1.
   30   -57.       840.       57.     21   22   23   -1.        1.    1.
   31    -57.      840.      -57.     21   22   23    -1.       1.   -1.
   32     57.      840.     -57.      21   22   23     1.       1.   -1.
   33    48.       960.      48.      24   25   26    1.        1.    1.
   34   -48.       950.       48.     24   25   26   -1.        1.    1.
   35    -48.      960.      -48.     24   25   26    -1.       1.   -1.
   36     48.      960.     -48.      24   25   26     1.       1.   -1.
   37    39.       1080.     39.      27   28   29    1.        1.    1.
   38   -39.       1080.      39.     27   28   29   -1.        1.    1.
   39    -39.      1080.     -39.     27   28   29    -1.       1.   -1.
   40     39.      1080.    -39.      27   28   29     1.       1.   -1.
   41    30.       1200.     30.      39    0   40     1.       0     1.
   42   -30.       1200.      30.     39    0   40   -1.        0     1.
   43    -30.      1200.     -30.     39    0   40     -1.      0    -1.
   44     30.      1200.    -30.      39    0   40      1.      0    -1.
   45    30.       1248.     30.      41   30   42    1.        1.    1.
   46   -30.       1248.      30.     41   30   42   -1.        1.    1.
   47    -30.      1248.     -30.     41   30   42    -1.       1.   -1.
   48     30.      1248.    -30.      41   30   42     1.       1.   -1.
   49    90.       1248.      0.       0   31   32    1.        1.    0
   50   -90.       1248.      0.       0   31   32   -1.        1.    0
   51    60.       1224.     15.      33   34   35    1.        1.    1.
   52   -60.       1224.     15.      33   34   35   -1.        1.    1.
   53    60.       1248.     15.      36   37   38    1.        1.    1.
   54   -60.       1248.     15.      36   37   38   -1.        1.    1.
   55   -60.       1224.     -15.     33   34   35    -1.       1.   -1.
   56    60.       1224.     -15.     33   34   35     1.       1.   -1.
   57    -60.      1248.     -15.     36   37   38    -1.       1.   -1.
   58    60.       1248.     -15.     36   37   38     1.       1.   -1.
 30000000.    .1     -15000.   20000.       4.
    1    1    5    1    1     10.
    2    2    6    1    1     10.
    3    3    7    1    1     10.
    4    4    8    1    1     10.
    5    5    9    1    2     10.
    6    6   10    1    2     10.
    7    7   11    1    2     10.
    8    8   12    1    2     10.
    9    9   13    1    3     10.
   10   10   14    1    3     10.
   11   11   15    1    3     10.
```

Table XVIII (cont'd)

12	12	16	1	3	10.
13	13	17	1	4	10.
14	14	18	1	4	10.
15	15	19	1	4	10.
16	16	20	1	4	10.
17	17	21	1	5	10.
18	18	22	1	5	10.
19	19	23	1	5	10.
20	20	24	1	5	10.
21	21	25	1	6	10.
22	22	26	1	6	10.
23	23	27	1	6	10.
24	24	28	1	6	10.
25	25	29	1	7	10.
26	26	30	1	7	10.
27	27	31	1	7	10.
28	28	32	1	7	10.
29	29	33	1	8	10.
30	30	34	1	8	10.
31	31	35	1	8	10.
32	32	36	1	8	10.
33	33	37	1	9	10.
34	34	38	1	9	10.
35	35	39	1	9	10.
36	36	40	1	9	10.
37	37	41	1	10	10.
38	38	42	1	10	10.
39	39	43	1	10	10.
40	40	44	1	10	10.
41	41	45	1	11	10.
42	42	46	1	11	10.
43	43	47	1	11	10.
44	44	48	1	11	10.
45	5	6	1	12	10.
46	6	7	1	12	10.
47	7	8	1	12	10.
48	8	5	1	12	10.
49	9	10	1	13	10.
50	10	11	1	13	10.
51	11	12	1	13	10.
52	9	12	1	13	10.
53	13	14	1	14	10.
54	14	15	1	14	10.
55	15	16	1	14	10.
56	13	16	1	14	10.
57	17	18	1	15	10.
58	18	19	1	15	10.
59	19	20	1	15	10.
60	17	20	1	15	10.
61	21	22	1	16	10.
62	22	23	1	16	10.
63	23	24	1	16	10.
64	21	24	1	16	10.
65	25	26	1	17	10.
66	26	27	1	17	10.
67	27	28	1	17	10.
68	25	28	1	17	10.
69	29	30	1	18	10.
70	30	31	1	18	10.
71	31	32	1	18	10.
72	29	32	1	18	10.
73	33	34	1	19	10.
74	34	35	1	19	10.
75	35	36	1	19	10.
76	33	36	1	19	10.
77	37	38	1	20	10.
78	38	39	1	20	10.
79	39	40	1	20	10.
80	37	40	1	20	10.
81	41	42	1	21	10.
82	42	43	1	22	10.
83	43	44	1	21	10.
84	41	44	1	22	10.
85	45	46	1	23	10.

Table XVIII (cont'd)

86	46	47	1	24	10.
87	47	48	1	23	10.
88	45	48	1	24	10.
89	1	6	1	25	10.
90	2	5	1	25	10.
91	2	7	1	25	10.
92	3	6	1	25	10.
93	3	8	1	25	10.
94	4	7	1	25	10.
95	4	5	1	25	10.
96	1	8	1	25	10.
97	5	10	1	26	10.
98	6	9	1	26	10.
99	6	11	1	26	10.
100	7	10	1	26	10.
101	7	12	1	26	10.
102	8	11	1	26	10.
103	8	9	1	26	10.
104	5	12	1	26	10.
105	9	14	1	27	10.
106	10	13	1	27	10.
107	10	15	1	27	10.
108	11	14	1	27	10.
109	11	16	1	27	10.
110	12	15	1	27	10.
111	12	13	1	27	10.
112	9	16	1	27	10.
113	13	18	1	28	10.
114	14	17	1	28	10.
115	14	19	1	28	10.
116	15	18	1	28	10.
117	15	20	1	28	10.
118	16	19	1	28	10.
119	16	17	1	28	10.
120	13	20	1	28	10.
121	17	22	1	29	10.
122	18	21	1	29	10.
123	18	23	1	29	10.
124	19	22	1	29	10.
125	19	24	1	29	10.
126	20	23	1	29	10.
127	20	21	1	29	10.
128	17	24	1	29	10.
129	21	26	1	30	10.
130	22	25	1	30	10.
131	22	27	1	30	10.
132	23	26	1	30	10.
133	23	28	1	30	10.
134	24	27	1	30	10.
135	24	25	1	30	10.
136	21	28	1	30	10.
137	25	30	1	31	10.
138	26	29	1	31	10.
139	26	31	1	31	10.
140	27	30	1	31	10.
141	27	32	1	31	10.
142	28	31	1	31	10.
143	28	29	1	31	10.
144	25	32	1	31	10.
145	29	34	1	32	10.
146	30	33	1	32	10.
147	30	35	1	32	10.
148	31	34	1	32	10.
149	31	36	1	32	10.
150	32	35	1	32	10.
151	32	33	1	32	10.
152	29	36	1	32	10.
153	33	38	1	33	10.
154	34	37	1	33	10.
155	34	39	1	33	10.
156	35	38	1	33	10.
157	35	40	1	33	10.
158	36	39	1	33	10.
159	36	37	1	33	10.

Table XVIII (cont'd)

160	33	40	1	33	10.
161	37	42	1	34	10.
162	38	41	1	34	10.
163	38	43	1	34	10.
164	39	42	1	34	10.
165	39	44	1	34	10.
166	40	43	1	34	10.
167	40	41	1	34	10.
168	37	44	1	34	10.
169	41	46	1	35	10.
170	42	45	1	35	10.
171	42	47	1	35	10.
172	43	46	1	35	10.
173	43	48	1	35	10.
174	44	47	1	35	10.
175	44	45	1	35	10.
176	41	48	1	35	10.
177	41	51	1	36	10.
178	42	52	1	36	10.
179	43	55	1	36	10.
180	44	56	1	36	10.
181	45	53	1	37	10.
182	46	54	1	37	10.
183	47	57	1	37	10.
184	48	58	1	37	10.
185	49	51	1	38	10.
186	50	52	1	38	10.
187	50	55	1	38	10.
188	49	56	1	38	10.
189	49	53	1	39	10.
190	50	54	1	39	10.
191	50	57	1	39	10.
192	49	58	1	39	10.
193	45	51	1	40	10.
194	46	52	1	40	10.
195	47	55	1	40	10.
196	48	56	1	40	10.
197	51	53	1	41	10.
198	52	54	1	41	10.
199	55	57	1	41	10.
200	56	58	1	41	10.
201	53	58	1	42	10.
202	54	57	1	42	10.
203	51	56	1	43	10.
204	52	55	1	43	10.
205	53	48	1	44	10.
206	47	54	1	44	10.
207	45	58	1	44	10.
208	46	57	1	44	10.
209	43	52	1	45	10.
210	41	56	1	45	10.
211	42	55	1	45	10.
212	44	51	1	45	10.
213	5	7	1	46	10.
214	6	8	1	46	10.
215	9	11	1	47	10.
216	10	12	1	47	10.
217	13	15	1	48	10.
218	14	16	1	48	10.
219	17	19	1	49	10.
220	18	20	1	49	10.
221	21	23	1	50	10.
222	22	24	1	50	10.
223	25	27	1	51	10.
224	26	28	1	51	10.
225	29	31	1	52	10.
226	30	32	1	52	10.
227	33	34	1	53	10.
228	34	36	1	53	10.
229	37	39	1	54	10.
230	38	40	1	54	10.
231	41	43	1	55	10.
232	42	44	1	55	10.
233	45	47	1	56	10.

Table XVIII (cont'd)

```
 234   46   48    1   56     10.
   1    1    1    1
   2    1    1    1
   3    1    1    1
   4    1    1    1
   2
  49   6000.    -20000.      0.0
  50   6000.    -20000.      0.0
   2
  49   6000.    -20000.      0.0
  50  -6000.    -20000.      0.0
   2
  49   6000.    -20000.      0.0
  50   3000.    -10000.      5000.
   2
  49   3000.    -10000.     -5000.
  50   3000.    -10000.      5000.
   2
  49  -3000.     10000.      5000.
  50  -3000.     10000.     -5000.
  49   200.
  50   200.
25.      25.       25.        25.       25.       25.       25.       25.
25.      25.       25.        25.       25.       25.       25.       25.
25.      25.       25.        25.       25.       25.       25.       25.
25.      25.       25.        25.       25.       25.       25.       25.
25.      25.       25.        25.       25.       25.       25.       25.
25.      25.       25.        25.       25.       25.       25.       25.
25.      25.       25.        25.       25.       25.       25.       25.
0.000001 .000001    .000001    .000001   .000001   .000001   .000001  .000001
0.000001  .000001    .000001    .000001  .000001    .000001  .000001  .000001
0.000001  .000001    .000001    .000001  .000001    .000001  .000001  .000001
0.000001  .000001    .000001    .000001  .000001    .000001  .000001  .000001
.000001  .000001   .000001    .000001   .000001   .000001   .000001   .000001
.000001  .000001   .000001    .000001   .000001   .000001   .000001   .000001
.000001  .000001   .000001    .000001   .000001   .000001   .000001   .000001
 100.     100.      100.      100.      100.      100.      100.      100.
100.     100.      100.       100.      100.      100.      100.      100.
100.     100.      100.       100.      100.      100.      100.      100.
100.     100.      100.       100.      100.      100.      100.      100.
100.     100.      100.       100.      100.      100.      100.      100.
100.     100.      100.       100.      100.      100.      100.      100.
100.     100.      100.       100.      100.      100.      100.      100.
120.     120.      111.       120.      111.      102.      240.      102.
93.      360.      93.        84.       480.      84.       75.       600.
75.      66.       720.       66.       57.       840.      57.       48.
960.     48.       39.        1080.     39.       1248.     1248.     90.
15.      1224.     60.        15.       1248.     60.       30.       30.
30.      30.
0.       0.        0.         0.        0.        0.        0.        0.
0.       0.        0.         0.        0.        0.        0.        0.
0.       0.        0.         0.        0.        0.        0.        0.
0.       0.        0.         0.        0.        0.        0.        0.
0.       0.        0.         0.        0.        0.        0.        0.
0.       0.
2000.    2000.     2000.      2000.     2000.     2000.     2000.     2000.
2000.    2000.     2000.      2000.     2000.     2000.     2000.     2000.
2000.    2000.     2000.      2000.     2000.     2000.     2000.     2000.
2000.    2000.     2000.      2000.     2000.     2000.     2000.     2000.
2000.    2000.     2000.      2000.     2000.     2000.     2000.     2000.
2000.    2000.
  49     1    1    -.3        .3
  50     1    1    -.3        .3
  49     1    2    -.3        .3
  50     1    2    -.3        .3
  49     1    3    -.3        .3
  50     1    3    -.3        .3
  49     1    4    -.3        .3
  50     1    4    -.3        .3
  49     1    5    -.3        .3
  50     1    5    -.3        .3
  49     2    1    -.3        .3
  50     2    1    -.3        .3
  49     2    2    -.3        .3
```

Table XVIII (cont'd)

50	2	2	-.3	.3
49	2	3	-.3	.3
50	2	3	-.3	.3
49	2	4	-.3	.3
50	2	4	-.3	.3
49	2	5	-.3	.3
50	2	5	-.3	.3

4.5

APPENDIX B

PROGRAM ORGANIZATION

A. DESCRIPTION

The program organization is laid out in the following flow charts. The main driver program is arranged to call a subdriver, XMSADT, and the optimizer of the user's choice. All changes for replacing an optimizer occur in MSADT. This allows for easy testing of several optimizers on the same problem.

XMSADT may be called from the main for input, analysis, and output. Printed output may vary as the user requires. A complete listing of all subroutines and their functions is given in Table .

Table XIX

ANALYSIS CONTROL

ANALYSIS ICALC=2

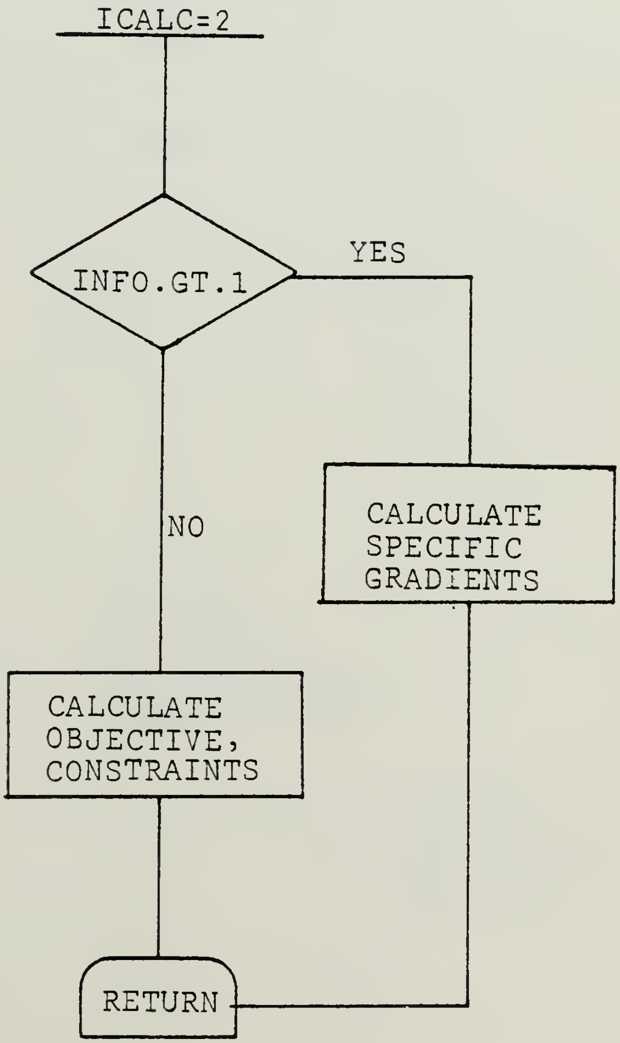

ICALC=2
INFO.GT.1
YES
NO
CALCULATE SPECIFIC GRADIENTS
CALCULATE OBJECTIVE, CONSTRAINTS
RETURN

Table XX

OUTPUT CONTROL

OUTPUT FOR INFO=0/1/2

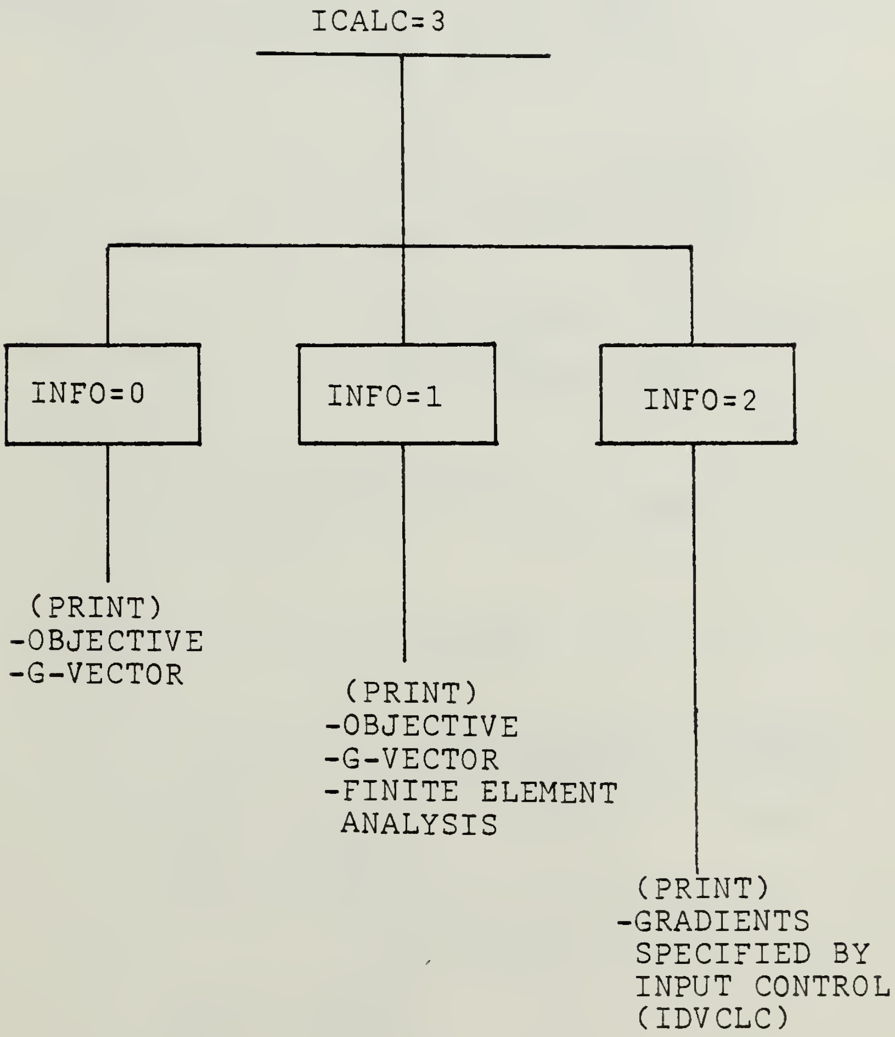


Table XXI

PROGRAM FLOW CHART

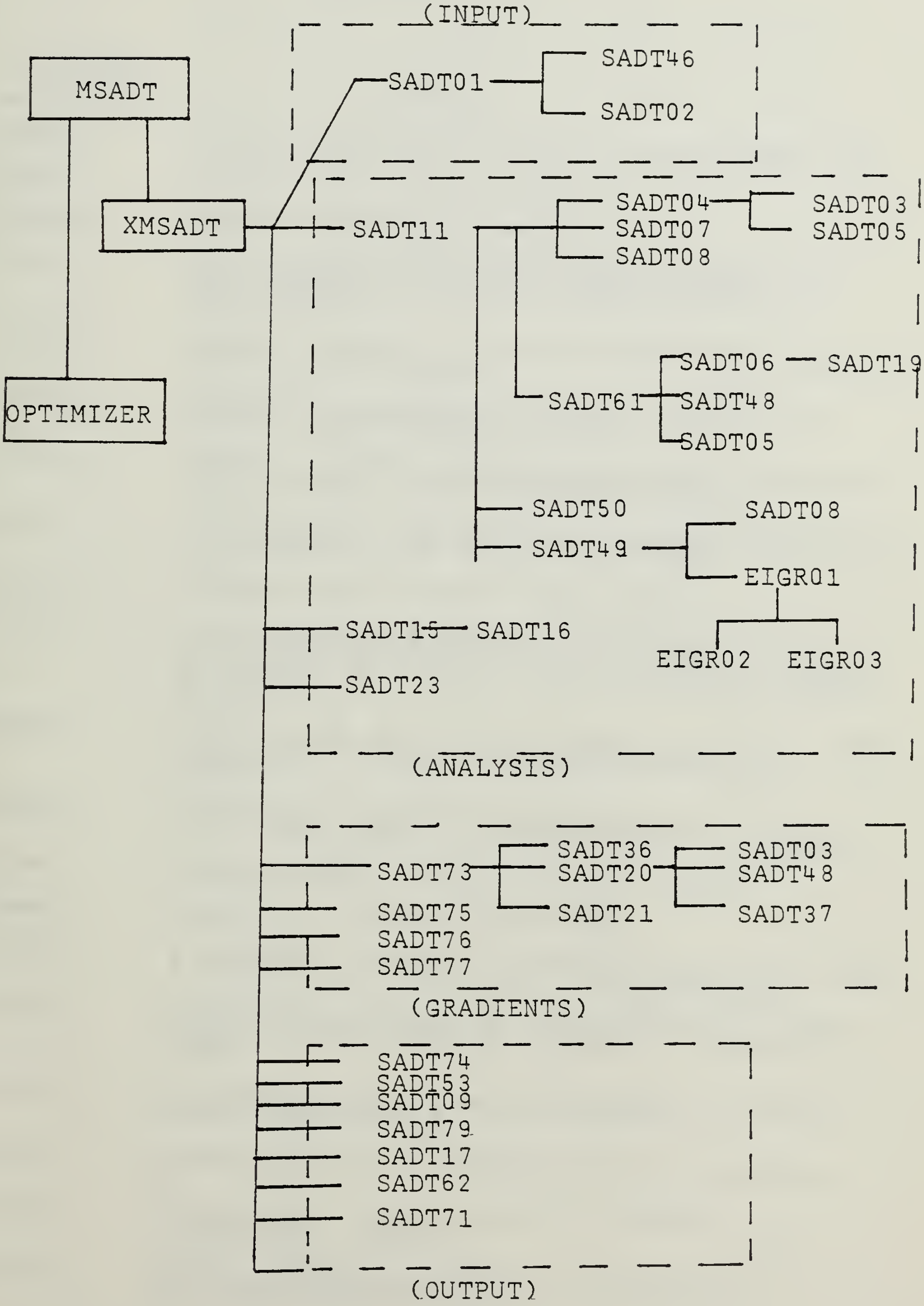


TABLE XXII

SUBROUTINE USES

FILENAME	TITLE
EIGR01	SOLVES EIGENVALUE PROBLEM |A-ALAMBD*B| X=0
EIGR02	SOLVES EIGENVALUE PROBLEM
EIGR03	SOLVES EIGENVALUE PROBLEM
SADT01	THIS ROUTINE READS AND PRINTS INPUT DATA AND ORGANIZES PSEUDO-DYNAMIC STORAGE ALLOCATION
SADT02	BUILDS VECTORS JC AND IIK FOR FINITE ELEMENT STRUCTURAL ANALYSIS
SADT03	BUILDS THE ELEMENT STIFFNESS MATRIX FOR TRUSS FINITE ELEMENT NO. II
SADT04	BUILDS ELEMENT STIFFNESS MATRICES AND ADDS THEM TO THE GLOBAL STIFFNESS MATRIX
SADT05	SUPERIMPOSES THE ELEMENT STIFFNESS VECTOR EK OF ELEMENT II ON THE GLOBAL VECTOR AK
SADT06	BUILDS GLOBAL LUMPED MASS MATRIX
SADT07	LU DECOMPOSES SYMMETRIC,POSITIVE-DEFINITE, SPARCE MATRICES,THE UPPER TRIANGLE OF WHICH IS STORED IN VECTOR AK WITH LEADING ZEROES OMITTED
SADT08	FORWARD AND BACK SUBSTITUTES TO YIELD A SOLN TO A SET OF LINEAR EQNS(DECOMPOSED W/ SADT07)
SADT09	PRINTS ALL JOINT DISPLACEMENTS FOR EACH LOAD CONDITION OF A FINITE ELEM. STRUCTURE
SADT10	PERFORMS TRUSS FIXED-GEOMETRY DESIGN
SADT11	ROUTINE TO ORGANIZE ANALYSIS
SADT14	CALCULATES PARTIAL DERIVATIVE OF TRUSS ELEM K MATRIX WRT COORD DOF I1 AT NODE J1
SADT15	CALCULATESS VALUES OF ALL DESIGN AND BEHAVIORIAL CONSTRAINTS AS DEFINED BY PROGRAM "SAD"
SADT16	CALCULATES STRESS IN BAR ELEMENT II UNDER LOAD CONDITION JJ
SADT17	PRINTS FORCES OR STRESSES IN BAR ELEMENTS
SADT18	CALCULATES GRADIENT INFO IN FINITE ELEM STRUCTURAL ANALYSIS
SADT19	ADDS ELEMEMENT MASS AA OF ELEMEMENT II TO GLOBAL MASS MATRIX

SADT20	CALCULATES THE PARTIAL DERIVATIVES OF THE DISPLACEMENTS WRT INDEPENDENT DESIGN VARIABLE II
SADT21	CALCULATES STRESS AND GRADIENT OF STRESS IN BAR ELEM II UNDER LOAD COND JJ GIVEN DISPLACEMENT VECTOR PL AND GRADIENTS OF THE DISPLACEMENTS IN VECTOR DU
SADT22	PERFORMS STRESS-RATIO DESIGN OF A FIXED GEOMETRY TRUSS
SADT23	CALCULATES WEIGHT OF TRUSS GIVEN AREAS AND LENGTHS
SADT26	CALCULATES THE GRADIENT OF WEIGHT WRT RECIPROCAL DESIGN VARIABLES
SADT31	CALCULATES GRADIENT INFORMATION AND STORES IN ARRAY TAY
SADT34	CONMIN EXTERNAL FOR TRUSS FIXED GEOMETRY DESIGN
SADT35	CALCULATES GRADIENT INFORMATION AND STORES IN ARRAY TAY
SADT36	CALCULATES (XEIG-T*AM*XEIG) FOR GRADIENT CALCULATIONS IN FREQUENCY CONSTRAINTS
SADT37	CALCULATES EIGENVALUE GRADIENT INFORMATION IN FINITE ELEMENT STRUCTURAL ANALYSIS AND DESIGN
SADT40	CALCULATES GRADIENTS OF DISPLACEMENTS WRT COORDINATE DESIGN VARIABLE II
SADT41	CALCULATES GRADIENT INFORMATION WRT COORDINATE VARIABLES
SADT42	CALCULATES GRADIENT OF WEIGHT WRT COORDINATE DESIGN VARIABLES
SADT43	CALCULATES GRADIENTS OF OBJECTIVE AND ACTIVE CONSTRAINTS IN OPTIMUM GEOMETRY DIRECTION FINDING PROBLEM
SADT44	PERFORMS TRUSS FIXED GEOMETRY DESIGN AND EVALUATES CONSTRAINTS
SADT45	PERFORMS TRUSS OPTIMUM GEOMETRY DESIGN
SADT46	READS INPUT INFORMATION FOR BAR ELEMENTS
SADT48	BUILDS THE ELEMENT MASS MATRIX FOR A TRUSS FINITE ELEMENT
SADT49	SOLVES REAL EIGENVALUE PROBLEMS USING THE SUBSPACE ITERATION METHOD
SADT50	BUILDS INITIAL SET OF BASIS VECTORS FOR EIGENSOLUTION BY REDUCED BASIS METHOD
SADT51	CALCULATES STRESS AND GRADIENT OF STRESS IN BAR ELEMENT II UNDER LOAD CONDITION JJ, GIVEN DISLPLACEMENTS CONTAINED IN VECTOR PL AND GRADIENT OF DISPLACEMENTS

	IN VECTOR DU
SADT52	PERFORMS 1-DIMENSIONAL SEARCH IN COORDINATE DESIGN SPACE
SADT53	PRINTS MEMBER INFORMATION FOR BAR ELEM
SADT54	CALCULATES AND PRINTS CENTER-OF-GRAVITY AND INERTIAL PROPERTIES OF FINITE ELEM STRUCTURE
SADT61	BUILDS GLOBAL MASS MATRIX
SADT62	PRINTS NEIG EIGENVALUES STORED IN EIGVAL, AND THEIR CORRESPONDING EIGENVECTORS STORED IN XEIG
SADT71	PRINTS G VECTOR OF CONSTRAINTS
SADT73	CALCULATES GRADIENT INFORMATION
SADT74	PRINTS TAY ARRAY OF GRADIENTS
SADT75	CALCULATES GRADIENT OF WEIGHT WITH RESPECT TO AREA DESIGN VARIABLES
SADT76	CALCULATES GRADIENT OF WEIGHT WITH RESPECT TO COORDINATE DESIGN VARIABLES
SADT77	CALCULATES GRADIENT INFORMATION
SADT79	PRINTS COORDINATE INFORMATION
MSADT	DRIVER PROGRAM FOR USING THE ABOVE SUBROUTINES. MSADT MAY BE COUPLED TO OPTIMIZER OF USER'S CHOICE.
XMSADT	SUBDRIVER PROGRAM FOR COUPLING SADT ROUTINES TO MSADT

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